GOEP: Annual Technical Progress Report

Cover page

GOEP Proposal number:	**GOEP**	**Date: 7/31/2008**
Project Title:	Clean Coal Processes: Vortecone® Modification for Emission Control at Coal-Fired Power Plants	
GOEP Grant Agreement #:	GOEP	
Name of PI:	Kozo Saito	
PI's Department:	Mechanical Engineering	
Name of Co-PI (s):	Abraham J. Salazar, Tianxiang Li	
Co PI's Department (s):	Mechanical Engineering	
Institution:	University of Kentucky	
Other Team members and Affiliation:		
Report Period:	07/01/07 to 06/30/08	
Total Grant Period:	07/01/06 to 06/30/08	
Report Type:	Final	

Table of Contents

Clean Coal Processes:
Vortecone® Modification for Emission Control at Coal-Fired Power Plants

Tianxiang Li, Abraham J. Salazar, and Kozo Saito *

Mechanical Engineering, University of Kentucky, 151 RGAN Bldg., Lexington, KY

Abstract

Overall objective of this research project is to conduct a serious of feasibility studies to evaluate the application of modified Vortecone@ technology in capturing coal-combustion fly ash. To achieve this goal, we have conducted experimental and numerical studied on performance of the modified Vortecone@ scrubber in capturing fly ash, and compared the results with these of a reference cyclone. The reference cyclone was selected according to the dimensions and parameters predicted by a simple cyclone model. The numerical simulation was carried on both reference cyclone and modified Vortecone@ scrubber. The numerical results show that the Vortecone@ scrubber could achieve 98%-99% capturing efficiency, about 10% higher than the reference cyclone predicted by the simple cyclone model. The energy savings by the Vortecone@ scrubber was at least 30% as compared with the reference cyclone. Experiments conducted on the TVA Shawnee fly ash show that the average capturing efficiency for the Vortecone@ scrubber was 99.82%, about 8% higher than experimental one on the reference cyclone, and the pressure drop on Vortecone@ scrubber was almost the same as the numerical results. These results verified that the developed computer code for the Vortecone@ was appropriate. However, the experimental results of capturing efficiency and pressure drop for the reference cyclone were better than predicted ones using simple cyclone model, implying that the cyclone performance was under-estimated by the simple cyclone model.

* PI: Tel: (859) 257-6336 x80639; Fax: (859) 257-3304
Email: saito@engr.uky.edu

Clean Coal Processes:
Vortecone® Modification for Emission Control at Coal-Fired Power Plants

*Tianxiang Li, Abraham J. Salazar and Kozo Saito**
Mechanical Engineering, University of Kentucky,151 RGAN Bldg., Lexington, KY

1. Introduction

There are more than 720 coal-fired power plants in the U.S. which produce 76 million tones of fly ash per year. The Environmental Protection Agency (EPA) is currently mandating reduction of particulate emissions by coal-fired power plants (CFPP) with a new focus on small particles less than 2.5 μm ($PM_{2.5}$). There is no current technology available particularly developed for effectively capturing these $PM_{2.5}$ and bonded mercury emissions from coal-fired power plants. These issues affect both Kentucky's coal industry as well as Kentucky's power plants that use coal to generate electricity. New green technology to recover small particulate and to remediate particulate escaped at transfer points would help make the continuous use of coal in power plants a viable option both economically and environmentally, as called for in Kentucky's *Comprehensive Energy Strategy*, developed by the Governor's Energy Policy Task Force embodying Governor's guiding principles for Kentucky's energy future.

1.1 Review of current emission control techniques

a. Greenhouse gas emission reduction

Greenhouse gas emissions from CFPP consist mainly of carbon dioxide (CO_2) released into atmosphere from fuel combustion. Although CO_2 concentration in clean air is less than 0.04 %, it has increased 25 % in the last century and may double by the end of the next century. CO_2 in air can absorb heat that would ordinarily radiate back into space from the earth surface, resulting in global warming. There are technologies available to capture CO_2 from power plant emissions but their costs are extremely high. Use reproducible energies such as wind, solar, hydro energy and the energies from agricultural products can reduce greenhouse gas emissions. However, minimizing the use of energy and natural resources is the most economical way to reduce greenhouse gas emissions.

b. Sulfur dioxide (SOx) and Nitrogen oxides (NOx) emission reduction

Sulfur dioxide (Sox) and nitrogen oxides (NOx) are pollutant gases. The former can create acid rain that harms environments and human activities, while the later harms human respiratory system. These gases are generated mainly by burning fossil fuels and from motor-vehicle exhausts. NOx formation can be controlled by using low NOx burners. Selective catalytic reduction (SCR) and non-selective catalytic reduction (NSCR) are approved to be appropriate devices for power plants and other industries to control NOx formation as well as to capture mercury in the flue gas lines. Fluidized-bed technology with flue gas recirculation can reduce both SOx and NOx formations. In the fluidized bed, Mixture of coal and limestone are injected into the combustion devices where fuel-sulfur reacts with limestone to produce solid calcium sulfate. Recirculation of flue gases and limestone particles can increase the consumption rate of limestone and reduce the peak flame temperature, leading to the reduction of NOx formation.

c. Mercury and other toxic compounds

* PI: Tel: (859) 257-6336 x80639; Fax: (859) 257-3304
Email: saito@engr.uky.edu

There are a number of technologies available to control emissions of mercury and other toxic compounds released from coal burning. For example, the devices that are used to control SOx, NOx and particulate can also remove mercury by injecting activated carbons into the flue gas line. The effectiveness of these technologies for mercury removal varies, depending on the characteristics of coal fired in the boilers and the configuration of the power plants. Because mercury is usually bonded on carbon particles, it is possible to remove mercury together with capturing particulate matter. Based on this concept, the modified Vortecone® technology, which was developed in this project to effectively collect fly ash from coal-fired power plants, may be able to remove mercury.

d. Particulate matter

Conventional devices such as cyclones and electrical precipitators can capture fly ash particles larger than 10 μm (PM_{10}) in diameter. Currently, there is no technologies available to efficiently capture the particulate less than10 μm.

Vortecone® technology, jointly developed by the University of Kentucky (UK) and Toyota Motor Corporation, was proven by full-scale and plant-site tests to be able to efficiently capture paint droplets less than 10 μm. An additional advantage of using Vortecone® in paint booths is the significant energy saving that was estimated in the order of 30%. Based on the successful story of Vortecone® applications, we believe that a modified Vortecone® technology may offer a great potential to capture fine particulate (PM_{10} or less) as well as mercury generated in CFPP.

1.2 Background of Vortecone® technology

The Vortecone® technology was jointly invented by Dr. Kozo Saito's research team at UK and Toyota engineers. This device is capable of capturing small (micron and sub-micron size) droplets of over-sprayed paints using special vortex chambers. In full-scale and plant site tests carried out by Toyota's plants in the U.S. and in Japan, Vortecone® technology was proved to be highly effective both in capturing paint droplets and reducing energy and operational costs as compared with current existing over-sprayed paint scrubber (see Fig. 1). This patented fully-developed and commercialized capturing scrubber was currently installed in seven Toyota's assembly plants both in U.S and Japan. The inventors are confident that Vortecone® can be adapted to effectively and economically capture small airborne particulate such as fly ash and sub-micron particulate matter.

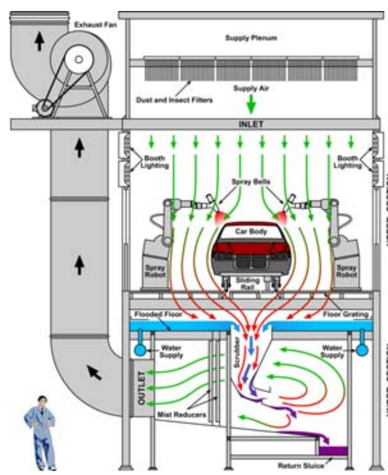

Figure 1. Schematic of paint booth

1.3 Successes of Vortecone® application in Toyota's paint booths

Toyota has invested more than $1,070,000 in the three-year project that leaded to the development of Vortecone® technology. It was installed in seven Toyota's assembly plants to capture over-spayed paints. The daily operations in these seven plants show that Vortecone® technology has a high volumetric capturing efficiency (> 99.6%) and lower pressure drop, and is capable to capture smaller paint particles as compared with current commercial scrubbers previously installed in these plants, resulting in substantial energy savings during booth operation. Figure 2 compares the pressure drop and mass penetration of the particles between Vortecone® and conventional scrubbers. The mass penetration is a more appropriate index than capturing efficiency because it shows the amount of particulate matter mass released. Results show that Vortecone® has one to two orders of magnitude less penetration than other commercial scrubbers commonly used in the field. In addition, Fig. 2 shows that the pressure drops generated during the operation using this new technology is substantially less than other scrubbers. Less pressure drop means energy savings. For example, it was estimated that in the year 2005, Toyota's Indiana plant saved $337,000 dollars in energy costs by using Vortecone® scrubber in their West B-line booth. In addition, considering less maintenance and cleaning costs, the total savings in this plant were estimated to be $4.4 millions. If we considering all seven Toyota plants that have installed Vortecone® scrubbers, the total savings were estimated to be $6.34 million dollars per year.

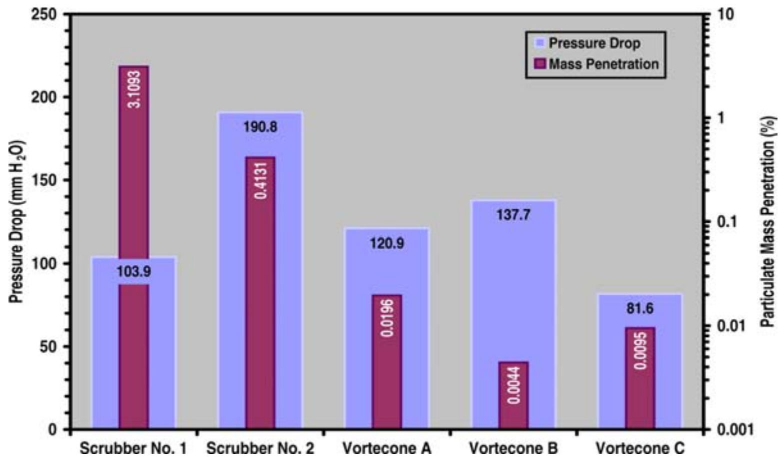

Figure 2. Comparison of Vortecone® performance with conventional scrubber as plotted the pressure drop and mass penetration of paint particles.

The Commonwealth of Kentucky has invested $300,000 indirectly in the Vortecone® project via the Painting Technology Consortium portion by KEDFA award to the Visualization and Virtual Environment Center, about 22% of the total project award. The public benefits due to invention of Vortecone® technology include 8 new jobs created at Trinity to build Vortecone® scrubber, 4 jobs for retaining, and 8 manufacturing jobs. If including the tax revenues (unknown), the total ration of public output to the investment is around 425 %.

2. Objectives and Technical Tasks

The overall objective of the project is to conduct a serious of feasibility studies to evaluate the application of already proved Vortecone® technology to capture fly ash, small particulate, and possibly the mercury emission from coal-fired power plants.

Table 1. Project Tasks and Timetable

Tasks	Quarter							
	1	2	3	4	5	6	7	8
Task 1. Site visit and data collection (4 months)	☺	☺						
Task 2. Analysis of plant site data (2 months)		☺						
Task 3a. Modification of computer code (8 months)			☺	☺				
Task 3b. Conduct simulation				☺	☺			
Task 4. Lab model experiments						☺	☺	☺
Task 5. Summarize the findings					☺			☺
Reports	☺	☺	☺	☺	☺	☺	☺	☺

Table 1 listed the project tasks and time schedule. The project includes 4 technical tasks. We started the site visit and data collection from coal-fired power plants (task 1). The data collected from plant visit was analyzed (task 2). In the meantime, the computer code previously used in the Vortecone® development was modified to satisfy the operation conditions in capturing fly ash and numerical simulations was conducted based on collected data and Vortecone® modification (task 3). Model experiments of capturing fly ash was conducted in our lab (task 4) to evaluate the feasibility of applying modified Vortecone® technology in fly ash capturing and to compare with the simulation. Quarterly and final reports were submitted to the GOEP office on time to report the results.

3. Characterization of Fly Ash

3.1 Fly ash analysis

We have visited two coal-fired power plants, the Paradise Fossil Plant located at Drakesboro and the Shawnee Fossil Plant in Paducah, KY. In the Paradise Plant, fly ashes were captured by electrostatic precipitators, while in Shawnee power plant fly ashes were collected by cyclone scrubbers. Three fly ash samples were collected from these power plants during our visit for analysis and ash characterization.

a. Appearance

Figure 3 shows the SEM image of typical fly ash (left) and the microscopic image of carbon burnt-out ash (right). Spherical particles shown in Fig. 3 (left) are the ash particles, whose main component is SiO_2. The irregular shapes are unburned carbons. In these power plants, low NOx burners were installed to lower the flame temperature, thus reduce NOx production, because NOx formation is sensitive to the peak flame temperature. However, lower flame temperature was traded with high unburned carbon content in fly ash.

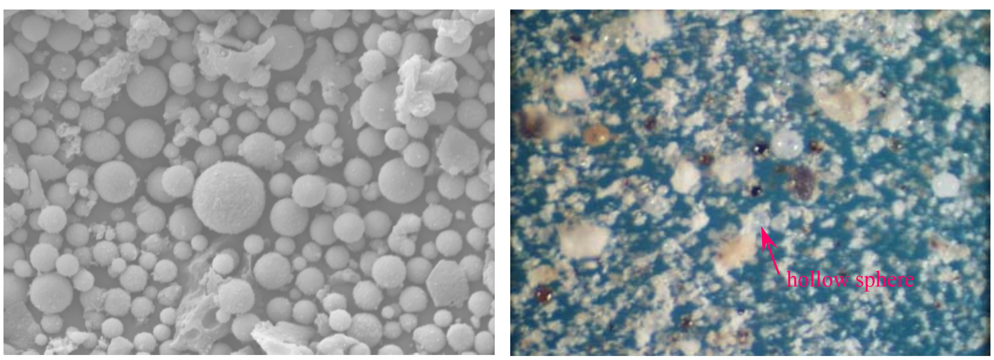

Figure 3. SEM image of coal-combustion fly ash (left) where spherical particles are ashes and irregular shapes are unburned carbons, and microscopic picture of carbon-burned out ash (right), showing hollow spheres, the value-added materials.

Shawnee power plant Unit 2 was installed low NOx burners to lower the NOx formation. The visual appearance of the fly ash is black, indicating high carbon content or Loss of Ignition (LOI). The measured LOI of Shawnee #2 fly ash sample was 9.21%, much greater than 3%, the standard LOI value, below which fly ash can be used as alternative material for cement production. Because of high LOI, the fly ash produced in Unit 2 was land-filled.

The picture shown on the right side of Fig. 3 is the fly ash sample after carbon burned out. It displays white hollow spheres, the value-added materials due to very light density. The hollow spheres are excellent thermal-resistant materials used for thermal insulation. Black particles were observed in the samples. Magnetic tests determined that these black particles were iron materials, typically existed in coals.

b. Size distributions

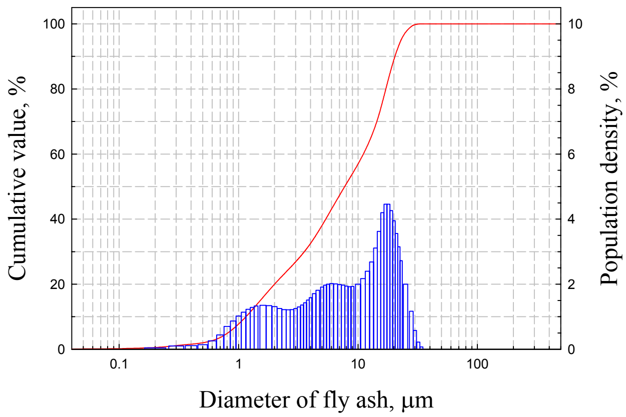

Figure 4. Size distribution and cumulative value for the Shawnee fly ash sample #2.

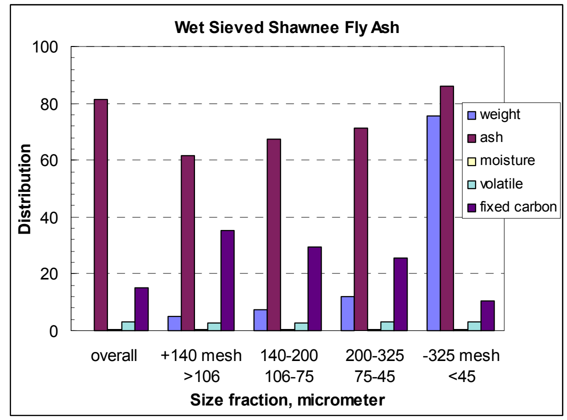

Figure 5. Weight distribution of wet-sieved Shawnee #2 ash and proximate analysis of each sieved fraction.

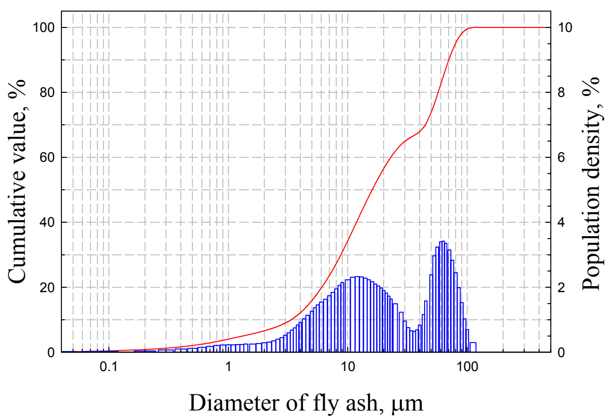

Figure 6. Size distribution and cumulative value for the Paradise ash #U2.

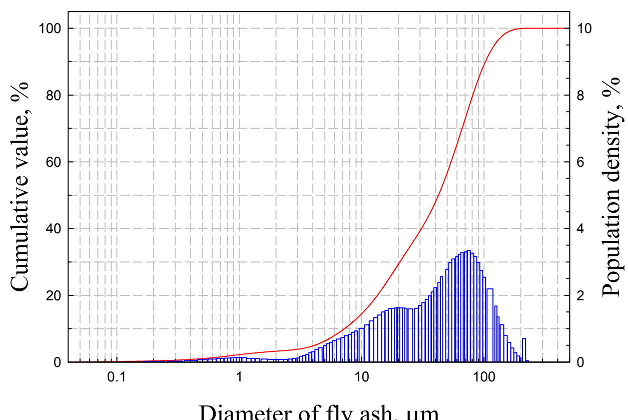

Figure 7. Size distribution and cumulative value for the Paradise ash #3S.

The size distribution of fly ash samples was measured by wet method using the Laser Particle Analyzer (model 1064, Cilas Comp.). The measured size distributions and the cumulative values are plotted in Fig. 4 for the Shawnee #2 ash sample. It can be seen that the majority of ash particles are in the size range between 1 to 20 µm. Cumulative plot vs. diameter provides the statistical variation of the particle diameter, that is, the diameter of particles at 10% population density is less than 1.15 µm, at 50% less than 7.74 µm, and at 90% less than 20.4 µm. The mean diameter of this ash sample is 9.62 µm.

The fly ash of Shawnee #2 was also wet-sieved and dried in four different size ranges (>106 µm; 106-75 µm; 75-45 µm; <45 µm). Their weight distribution and the approximation analysis of original and each of sieved fractions were measured and the results are shown in Fig. 5. It can be seen that more than 75% of weight was concentrated on the fine particles < 45 µm, in which 85% of component is silica. Fixed carbon and volatile (LOI) are around 14%, slightly greater than that measured in dry-state. This because wet-sieving processes may loss fine silica particles less than 1 µm, causing LOI relatively increase.

Four fly ash samples were collected from Paradise Power Plant in the units 2 (#U2) and 3 (#3S). Both units installed the Selective Catalytic Reduction (SCR) system for NOx reduction and used wet lime scrubbers for SOx removal. Unit 3 uses cyclonic burners so that it can burn large coal particles (up to 0.25 inch diameter) instead of pulverized coal. Because of wet limestone added, produced fly ashes contain large trunks of mixture of fly ashes and limes so that mechanical screens have to be used to remove trunks before the fly ash was captured in cyclones and precipitators. These large trunks are not interested in our research so that we did not analyze these trunks.

Visual observation displays that ash sample of Paradise #U2 has clay-like color with large particles exceeded the size limit that the equipment can measure so that we screened the sample to remove the particles larger than 90 μm prior the size analysis, leaving fine particles to analyze the size distribution, as shown in Fig. 5. The removed large particles weigh 44.8 % of total samples. The LOI of this sample is 16.94 %, higher than Shawnee #2 and Paradise #3S samples. Figure 5 shows that screened ash was in the size range of 2 – 30 μm. The cumulative value indicates that the diameter of the fly sample at 10 % population is less than 3.35 μm, 50 % population is less than 16.0 μm, and 90 % population is less than 70.17 μm. The average diameter of total fly ash sample is 28.52 μm. The Shawnee #2 fly ash samples were used for our experiments and numerical simulation.

Table 2. Standard cyclone dimensions

Body diameter	$D/D = 1.0$
Height of inlet	$H/D = 0.5$
Width of inlet	$W/D = 0.25$
Diameter of gas exit	$D_e/D = 0.5$
Length of Vortex finder	$S/D = 0.625$
Length of body	$L_b/D = 2.0$
Length of cone	$L_c/D = 2.0$
Diameter of dust outlet	$D_d/D = 0.25$

Table 3. Cyclone parameter dependence

Air flow rate (acfm)	Inlet velocity (fpm)	Pressure drop (inch w)
5,000-8,000	4,670-6,465	16.1-7.1
8,000-11,500	4,530-6,510	15.1-5.5
8,000-13,000	4,530-7,360	18.8-7.0

The Paradise #3S fly ash sample is visually brownish and the LOI is 12.18 %. This sample also contains coarse ash particles so that we removed them prior analysis. The coarse particles accounts for 34.78 % by weight in the total ash samples. The size distribution and cumulative value of the screened fine fly ash is shown in Fig. 6. The great population of this ash sample is between 3-90 μm. The cumulative value indicates that diameter of fly ash particles at 10 % population is less than 7.25 μm, 50 % population is less than 42.44 μm, and 90 % population is less than 102.89 μm. The average diameter of the sample is 49.36 μm. Realizing that Paradise unit 3 uses cyclonic burners and burn crushed coal up to 0.25 inch diameter instead of pulverized fine coal, it is reasonable that produced ash has relatively large size.

3.2 Evaluation of cyclone performance

Cyclones are the widely used devices in industrial gas-cleaning and particle capturing. In the coal-fired power plants, cyclones are used to capture fly ash because of its simple geometry, low costs of fabrication and modulate capturing efficiency. In the Shawnee power plant, cyclones were installed in each unit of power lines to capture fly ashes. Because of similar the dynamic and operational principles between Vortecone@ technology and cyclones, it is worth to compare performance of Vortecone@ with cyclones, instead with electric precipitators that operate in totally different ways.

a. Determination of cyclone geometry and operational conditions

In order to compare the performances of Vortecone® and reference cyclone, it is necessary to determine cyclone geometry of typical conventional cyclone as shown in Fig. 7. The parameters to be determined are dimensions, inlet and outlet velocities, gas resident

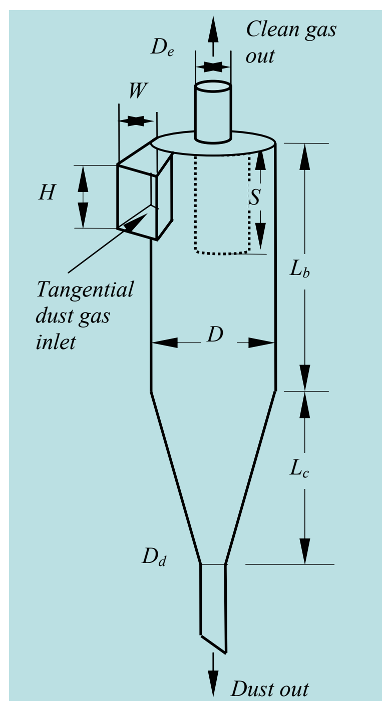

Figure 7. Schematic of a typical conventional cyclone.

times, cut diameters of particles, and operational efficiency. Cooper and Alley (1986) summarized the imperial dimensional relations between each unit of standard cyclones. Table 2 lists cyclone parameter correspondence from selected cyclone models. In their estimations, the body diameter was considered the base parameter, which was determined based on the flow rate in cyclone inlet. All other dimensions were calculated from their relation with the body diameter.

In the design of a conventional cyclone, three basic parameters are particularly important that are flow rate, inlet velocity and pressure drops. Their dependence is shown in Table 3. For our reference cyclone, the flow rate obtained from Shawnee plant was 10,156 acfm, the corresponding inlet velocity is in the range of 4530 to 7360 fpm, and the pressure drop is between 18.8 and 7.0 inch water. Based on this estimation, we choose 1.5 m diameter of body diameter as base dimension. However, this dimension is too large to be operated in laboratory. We use scale-modeling technique to scale down the dimensions of the reference cyclone. Consequently, the modified Vortecone[@] was also correspondingly scale-down to satisfy the operation in laboratory and comparison the results from two devices.

b. <u>Parameter determination</u>

A very simple model (Cooper and Alley, 1986) can be used to determine the effects of cyclone geometry and performance on the operational efficiency. In this model, it was assumed that gas in the cyclone spins through a number of revolutions N_e in the outer vortex.

$$N_e = \frac{1}{H}(L_b + \frac{L_c}{2}) \tag{1}$$

The average inlet velocity V_{in} is determined by the gas flow rate Q and inlet geometry

$$V_{in} = Q / WH \tag{2}$$

where W and H are the width and height of the inlet. The gas resident time in the cyclone is determined the equation

$$\Delta t = \pi DM\, N_e / V_{in} \tag{3}$$

which was used to evaluate the residence time of the particles in the outer vortex. To evaluate the performance of a cyclone in capturing particles, it was defined a 50% cut diameter d_{pc} as the smallest particles that the cyclone can be captured with 50% efficiency. According to Lapple (1951), 50% cut diameter was determined by

$$d_{pc} = \left[\frac{9 \mu W}{2\pi N_e V_{in} (\rho_p - \rho_g)} \right]^{1/2} \tag{4}$$

The particle terminal velocity V_{ex} is the function of particle diameter. Because particles are subjected to the centrifugal force, the terminal velocity for the particle in 50% cut diameter is expressed as

$$V_{ex} = \frac{(\rho_p - \rho_g) d_{pc}^2 V_{in}^2}{9 \mu D} \tag{5}$$

The efficiency of particles in jth size range is given by

$$\eta_j = \frac{1}{1 + (d_{pc} / d_j)^{1/2}} \tag{6}$$

and the overall the overall efficiency for all particles captured by cyclone is the weighted average of the collection efficiencies for all size ranges, and is given by

$$\eta = \frac{\sum \eta_j m_j}{m} \tag{7}$$

Using this simple cyclone model, the inlet velocity for the reference cyclone is 21.3 m/s and gas resident time is 1.22 sec. According to Eq. 4, the particles with 50% capture efficiency (50% cut diameter) is 6.9

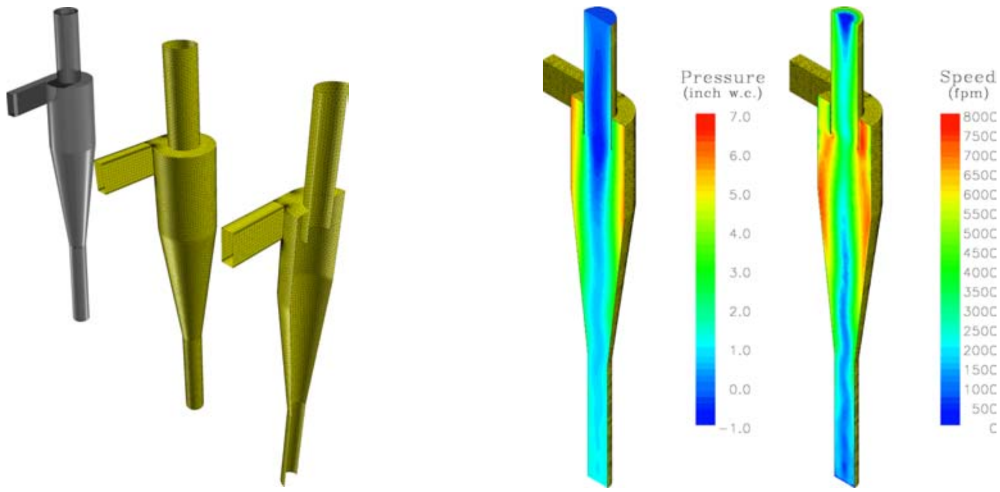

Figure 8. Reference cyclone: CFD geometry and mesh (left), calculated pressure drop and speed (right).

μm with the particle terminal velocity 0.123 m/s. The overall efficiency for this reference cyclone using Shawnee fly ash is 88.25%. These parameters are used in the numerical simulation for both cyclone and Vortecone®.

4. Numerical Simulation

4.1 Modification of Vortecone® computational code

Modification of current UK Vortecone® computer code used for capturing over-sprayed paint particles was carried out to satisfy changed conditions for capturing fly ash. A reference cyclone was also simulated for comparison. The CFD geometry and mesh of reference cyclone is shown in Fig. 8 (left). The calculation uses hybrid grid with complex geometries. With Lagangian-Eulerian simulation approach, the k-ω turbulence model was applied together with 2nd order upwind to treat convective terms. The multi-grid solution strategy and scrubbing water modeling are also used in the Vortecone® simulation. All equipment tested was at 10,156 acfm flow rate to match the industrial need. Figure 8 (right) is the results of calculated pressure drop and speed of this reference cyclone.

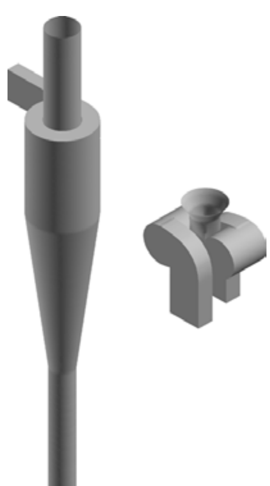

Figure 9. Size comparison of cyclone and Vortecone@ with the same operational flow rate.

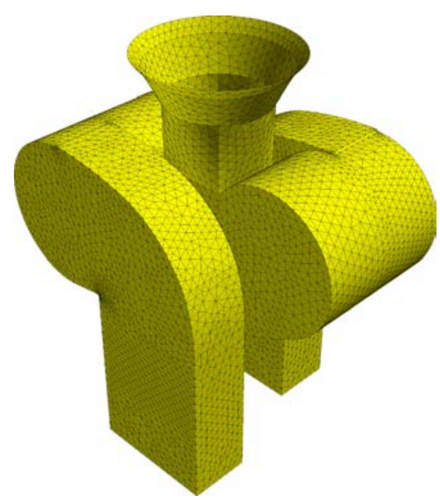

Figure 10. Vortecone@ geometry and CFD mesh.

Figure 9 shows the schematic comparison of geometry and dimensions between the reference cyclone and the modified Vortecone$^{@}$ scrubber, both of which operated in the same flow rate. The comparison shows that at the same inlet flow rate, Vortecone$^{@}$ is much smaller than cyclone. This is one of the advantages in application of Vortecone$^{@}$ technology in capturing fine particles.

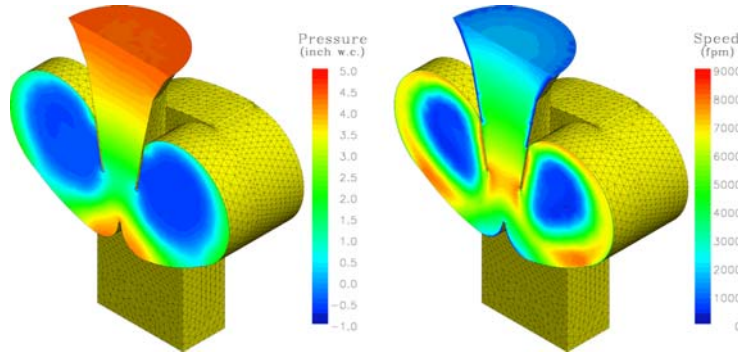

Figure 11. Calculated pressure drop and speed for original Vortecone® A configuration.

Figure 10 shows the CFD geometry and mesh. The calculation uses same methods as the cyclones except the geometry of Vortecone$^{@}$ is much complicated than that of cyclone so that it needs more grid for the calculations.

4.2 <u>Simulation results</u>

Simulation was also conducted for three types modified Vortecone$^{@}$, original Vortecone$^{@}$ A, modification Vortecone$^{@}$ A No. 1, and modification Vortecone$^{@}$ A No. 2. The calculated pressure drop and flow speed for the Vortecone$^{@}$ A original model was show in Fig, 11. The results of pressure drop and flow speed for the modified Vortecone$^{@}$ A are shown in Fig. 12 for model No.1 (top) and model No.2 (bottom), respectively.

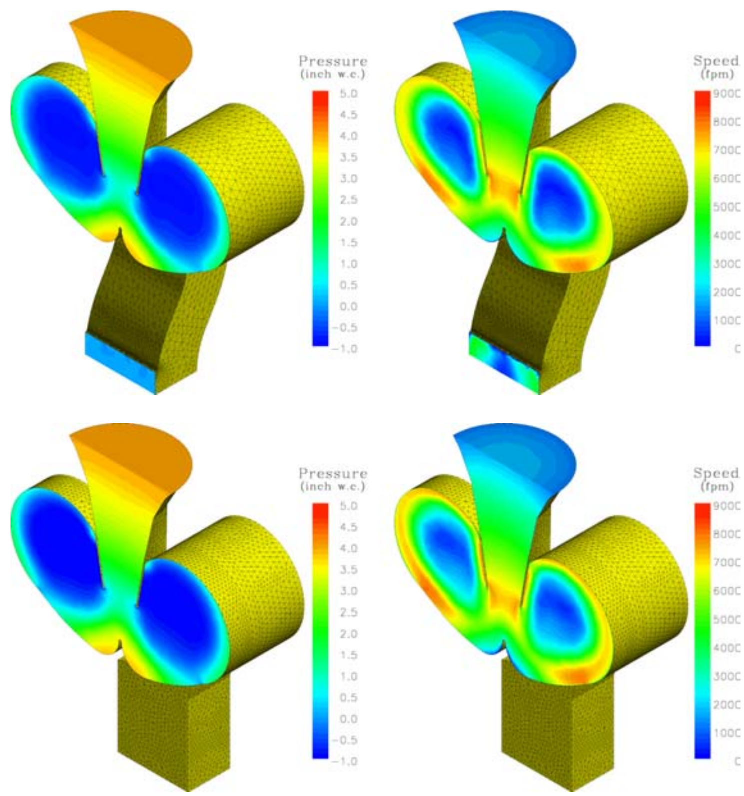

Figure 12. Calculated pressure drop and speed for modified Vortecone® A No.1 (top) and modified Vortecone® A No.2.

The comparison between cyclone and the three Vortecone® configurations in terms of the pressure drop (ΔP) and the particulate matter mass penetration is listed in Table 4. The calculated pressure drop (ΔP) is based on our CFD results. Operational cost of the device is directly proportional to the energy per unit time (the power) consumed, which is in turn directly proportional to the pressure drop times the flow rate. Therefore, the higher the pressure drop the higher the operational cost and energy consumption of the device.

Completed simulation tests verified that Vortecone® A is 30% more energy efficient than the reference cyclone. A slightly modified Vortecone® A (modification No. 2) can be 37 % more energy efficient. The value of penetration for the Vortecone® A configurations was found between 7.6 – 12.6 times lower than that estimated for the cyclone.

Table 4. Comparison of performance of Vortecone@ with reference cyclone.

Device	Cyclone (installed)	Vortecone® A (original)	Vortecone® A (mod. No. 1)	Vortecone® A (mod. No. 2)
ΔP (inch w.c.)	6.395* (baseline)	4.468 (30.12% ↓)	4.077 (36.25% ↓)	3.999 (37.47% ↓)
Penetration (%)	11.75 (baseline)	1.55 (7.6 times ↓)	1.90 (6.2 times ↓)	0.93 (12.6 times ↓)
η = Efficiency (%)	88.25	98.45	98.10	99.07

5. Experiments

In order to performance ash capturing experiments in laboratory, the reference cyclone and modified Vortecone@ scrubber need to be scale down. We developed scaling law to construct two scale-down model experimental apparatus. According to scaling law, the model experiments of cyclone were scaled down from the prototype in Shawnee power plant, unit 2. Consequently, the Vortecone@ scrubber was also scale down in the same ratio and modified from its original versions applied in Toyota's paint booths. Two laboratory model test apparatus were constructed; one small scale and one large scale collection system.

These systems were designed based on the scaling laws and predicted simulation results. Figure 13 are the photos of the two system setup. Both consist of three units: working unit (cyclone and Vortecone@), pneumatic transport lines and vacuum suction assemble. Because the vacuum suction assemble has to work in full load all the time, a bypass line was built to allow vacuum operation in full load when low flow rate of inlet air is required. The working unit is the particle capturing scrubbers. The reference cyclone (CV06, ClearVue Cyclones, Inc) and modified Vortecone@ can be easily replaced each other. During the experiments, pressure drops were measured in three locations, between scrubber inlet and outlet, exhaust pipe and bypass line. The model experiments of capturing coal-combustion fly ash were conducted using Shawnee #2 fly ash. Before each test, around 500 g of fly ash was weighted and feed from the scrubber inlet. The feeding time was recorded to calculate feed rate. After experiments, the

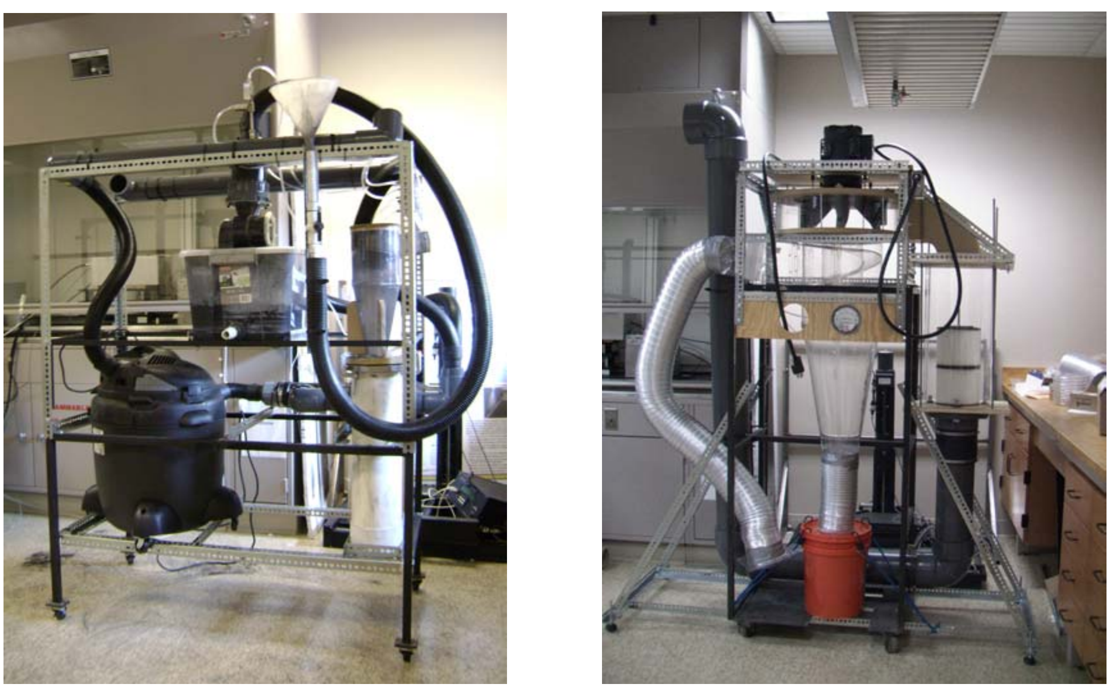

Figure 13. Experimental setup of small scale capturing system (left) and large scale capturing system (right).

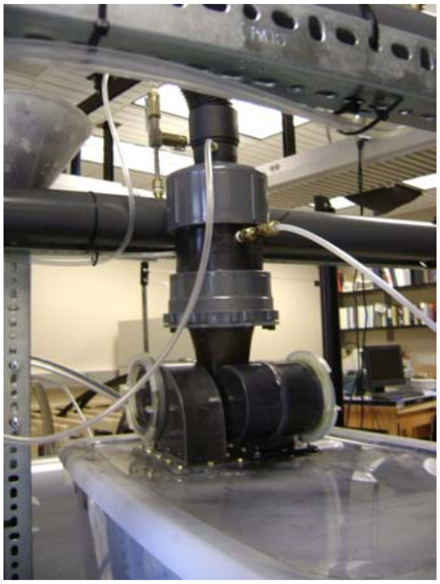

Figure 14. Vortecone$^{@}$ scrubber assemble

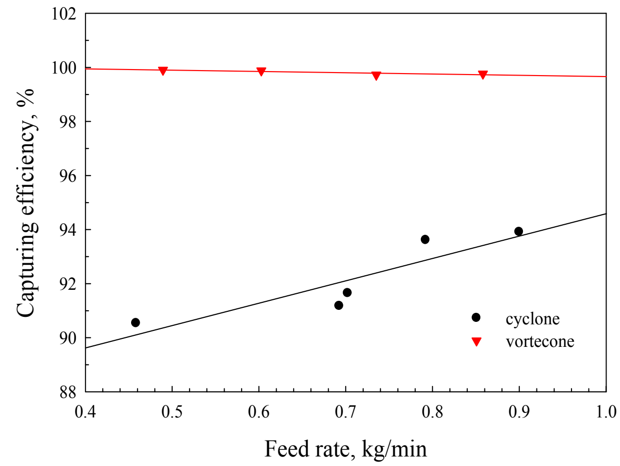

Figure 15. Comparison of capturing efficiency for the reference cyclone and the modified Vortecone$^{@}$ scrubber in capturing fly ash.

collected ash was weight again to determine weight loss and collection efficiency. Different feeding rates were tested to determine the effect of feeding rate on the pressure drops.

6. Results and Discussion

The model experiments of capturing coal-combustion fly ash were conducted using Shawnee #2 fly ash. In each experiment, around 500 g of fly ash was weighted and tested. Figure 14 is the picture of modified Vortecone$^{@}$ scrubber installed in the system and under operation. The capturing efficiency of the reference cyclone and the modified Vortecone$^{@}$ is plotted in Fig. 15 as the function of feed rate. The results show that for cyclone operation, the efficiency increases with the increase in feed rate. The efficiency is between 90% and 94%, higher than our prediction explained in the previous text. For the Vortecone$^{@}$ operation, the capturing efficiency is almost constant as feed rate increases. The average efficiency is 99.82%, around 8% higher that that of cyclone performance. This efficiency is also slightly higher than the results by numerical simulation, in which the efficiency for model No.2 is 99.07%.

The average pressure drop of Vortecone$^{@}$ scrubber between flow inlet and outlet was 3.82 inch H_2O, slightly lower than of cyclone, which was around 4.0 inch H_2O. The experimental measured pressure drop for Vortecone$^{@}$ performance is close to the prediction in numerical simulation, while the measure pressure drop for cyclone performance is lower that numerical results, which was 6.4 inch H_2O. Under-predicted cyclone performance may be because the imperial model created by Cooper and Alley was too simple. However, this simple model is useful in the design of conventional cyclones.

Conclusion

The overall objective of this project is to conduct a serious (experiments and simulations) of feasibility studies to evaluate the application of modified Vortecone$^{@}$ technology in capturing coal-combustion fly ash. This is the extended application followed by the success of Vortecone$^{@}$ application in capturing waste paint droplet in Toyota's paint booths. In order to achieve this goal, we have experimentally and numerically studied the performance of modified Vortecone$^{@}$ scrubber in capturing coal-combustion fly ash, and compared the results with a reference cyclone. The fly ash samples obtained from coal-fired power plants were characterized for size distributions, including dry and wet-sieved fractions, LOI, and approximation analysis. The reference cyclone was designed based on the evaluation by a simple cyclone model to determine basic geometry. Using this cyclone model, the cyclone performance was evaluated. Modification of current Vortecone® computer code was conducted to allow comparison of Vortecone® performance with that of the reference cyclone in terms of energy consumption and collective efficiency. Using modified computer code, we have conducted numerical simulation for both cyclone and different types Vortecone@ scrubbers. The simulation results show that the modified Vortecone@ technology can be applied to capturing coal-combustion fly ash emitted from power plants. We also conducted laboratory experiments using both cyclone and Vortecone@ scrubber. The experimental results show that average efficiency for Vortecone@ was 99.82%, around 8% higher than that using the reference cyclone. The measured pressure drop for the Vortecone@ was around 3.83 inch H_2O, very close to the simulation results. The experiments verified that modified computer code was a useful tool in predict the performance of capturing fine particles. However, the experimental results show that measure results of capturing efficiency and pressure drop for the reference cyclone were better than predicted results using simple cyclone model. Overall, based our experimental and numerical results, the modified Vortecone@ technology was feasible in capturing fly ash with high efficiency and low pressure drop, implying that energy can be saved if use Vortecone@ technology to replace conventional cyclones in capturing fly ash produced in coal-fired power plants, which saves energy and costs as well as benefits the environment.

References

1. Russel W. Bessette, Measuring the economic impact of university-based research, *J. of Technology Transfer*, 28:355-361, 2003. [NY state office of science, technology and academic research].
2. A.N. Link, A suggested method for assessing the economic impacts of university R&D: including identifying roles for technology transfer officers, *J. of the Association of University Technology Managers*, XI, 1-17, 1999.
3. C.D. Cooper and F.C. Alley, Cyclones, Adapted from Air Pollution Control, 1986.

Supplemental Information

A. Status of project personnel (hired, started, continuing, etc).
Please include: First, last name, academic level, gender, ethnicity, department, university/organization affiliation, and status for each person.

- Dr. Kozo Saito (PI), Professor, Male, Dept. of ME, UK, supervise the project
- Dr. Abraham Salazar, (Co-PI), Assistant Professor/Res, Male, Dept. of ME, UK, modeling and numerical simulation
- Dr. Tianxiang Li (Co-PI), Assistant Professor/Res., Male, Dept. of ME, UK, experiments
- One graduate student will join the team.

B. **Grant and contract proposals submitted.**
Please include: *Agency, PI, Co-PI, project title, $ requested, date submitted for each proposal.*

- N/A

C. **Grant and contract awards received .**
Please include: *Agency, PI, Co-PI, project title, $ awarded, date received, start date of grant and length of grant for each grant.*

- None

D. **Manuscripts submitted/published.**
Please include: *Journal, article title, authors, and status or date accepted, & journal reference for each.*

- No manuscripts related to this project are submitted/published.

E. **Invention disclosures, filing of patent applications, and technology transferred.**
Please include: *Application type, title, inventors, date applied, assigned number, and status of each application, and details of technology transferred, if any.*

- Intellectual property disclosure was submitted to University of Kentucky on 7/23/2007
  Title: Modified wet scrubber to capturing coal-combustion fly ash
  Inventors: Kozo Saito, Abraham J. Salazar, Tianxiang Li, Mark H. Pittman
  Intellectual property was proved.

F. **New collaborations.**
Please include: *First/Last name, university/organization affiliation, department, gender, ethnicity, collaboration type (i.e. university/industry), and nature of collaboration for each.*

- Paradise fossil plant, TVA, Drekesboro, KY
- Shawnee fossil plant, TVA, Paducah, KY

G. **Presentations.**
Please include: *Conference title or location description, city, state, date, presentation title, type, and presenters for each.*

- None

H. N/A

I. Potential application of the research
Vortecone® technology can also apply to pollutant controls in steel manufacturing (Nippon Steel has already shown their strong interests in Vortecone® clean environmental technology).